Multi-Technique Studies of Ionospheric Plasma Structuring

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LONG-TERM GOALS

Understanding physical processes that leads to plasma structuring in the equatorial, mid and high-latitude ionosphere. Identifying the effects of such variability, generally known as ionospheric space weather, on the operation of various communication, navigation and surveillance systems.

OBJECTIVES

Establish major drivers that lead to structured ionospheric plasma in equatorial, mid and high-latitude regions. Investigate cascading of plasma structuring from large (~ hundreds of km) to small scales (~ tens of m), which cause outages in space-based communication and GPS-based navigation systems.

APPROACH

Investigations on the impacts of magnetic storms on the mid-latitude ionosphere and connections to perturbations in the equatorial ionosphere were carried out with the study of the intense magnetic storm that occurred on November 20, 2003. The diagnostic techniques used were measurements of TEC fluctuations using about 250 GPS dual-frequency stations within the US to determine structuring at tens of km scales. Coordinated data of sub-auroral polarization streams were obtained from DMSP F-13, while equatorial plasma structuring measurements were obtained from the DMSP F-14 satellite. The PI is one of the primary persons working on this problem with scientific colleagues providing the scintillation and DMSP data analysis (Santimay Basu, Keith Groves, Fred Rich of AFRL and Eileen MacKenzie and Pat Doherty of Boston College). Some theoretical ideas on plasma instabilities were provided by Mike Keskinen of NRL.

WORK COMPLETED

The above analysis has been completed and a manuscript is being prepared for publication in the Journal of Geophysical Research. Two presentations on the comparison of several storms and their impacts on GPS navigation have been made at the Fall AGU Meeting in San Francisco in December, 2005 and the COSPAR Meeting in Beijing in August 2006.

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RESULTS

Background.

The response of the earth's ionosphere to intense magnetic storms has engaged the attention of ionospheric and magnetospheric physicists, as well as modelers for several decades. In addition, systems engineers have been interested in these effects as the ionospheric plasma structures that are formed during magnetic storms often profoundly impact satellite communication and navigation systems. During major magnetic storms, the interaction between the solar wind and the magnetosphere under IMF Bz southward conditions causes a change in the Region-1 current leading to a sudden increase in the dawn to dusk polar cap potential. The Region 2 currents, associated with an inner magnetospheric electric field directed in the dusk to dawn direction, are no longer able to shield the middle and equatorial latitudes from the high latitude electric fields. This results in an instantaneous penetration of an electric field from high latitude to the middle and the equatorial ionosphere. Nishida et al. (1966) first provided the evidence for the prompt penetration of electric field by noting geomagnetic variations in the equatorial region in response to variations in the interplanetary electric field. This prompt penetration electric field is eastward during the daytime to the dusk sector and westward in the midnight to the dawn sector (Jaggi and Wolf, 1973; Spiro et al., 1988; Fejer et al., 1990). During the Bastille Day storm, a sharp decrease in the SYM-H (1-min resolution Dst) index occurred between 2000 - 2100 UT causing an eastward penetration electric field to lift the ionosphere and form plasma bubbles and bite-outs in the F-region over the South Atlantic and Brazilian sectors at local dusk (Basu et al., 2001b). At the same time, in the post-midnight sector the penetration of a westward electric field caused the ionospheric F-region over India to drift downwards and collapse through recombination (Sastri et al., 2002). The characteristic time scale for shielding was found to be less than an hour (Spiro et al., 1988). However, it was shown by Fejer et al. (1990) that the duration of this prompt penetration phase can exceed an hour due to changes in the magnetic field configuration resulting from changes in the polar cap potential. On occasions, when the IMF Bz remains southward for several hours and the magnetic activity continues to intensify, the prompt penetration of the electric field into the low latitude ionosphere may persist for many hours as has been shown by Huang et al. (2005, 2006).

In addition to the prompt electric field penetration, the storm time neutral winds caused by the Joule heating at auroral latitudes develop a disturbance dynamo electric field through the action of the ionospheric dynamo process described by Blanc and Richmond (1980) and observed by Fejer and Scherliess (1995). These studies establish that at low latitudes, the dynamo effect of the perturbed wind causes the equatorial anomaly to be weaker on the dayside and enhanced on the nightside. The dynamic and electrodynamic response at low latitudes have been investigated by Fuller-Rowell et al. (2002) by using a coupled three-dimensional model of the thermosphere, ionosphere, plasmasphere and elctrodynamics (CTIPE). In addition to confirming the diurnal variation of low latitude electric fields outlined by the theory of Blanc and Richmond (1980), this model portrayed a rather prompt response of the equatorial ionosphere due to the effects of mid-latitude wind surges. Modeling the disturbance dynamo phase is complicated because these electric fields have to operate on an ionosphere that has been modified by the initial prompt penetration field (Maruyama et al., 2005). Our understanding of this complex interaction can be advanced by global ionospheric modeling of many storms and model validation with observations at globally dispersed locations (Fejer et al., 1990; Fejer and Scherliess, 2001; Fejer and Emmert, 2003; Basu et al., 2001a, b, 2005a). .

Discussion.

The isolated and very large magnetic storm that occurred on November 20, 2003 provides a good example of some of the unresolved issues mentioned above. Foster et al. (2005) presented a global view of large-scale ionospheric disturbances during the main phase of this storm. They found that the low-latitude, auroral, and polar latitude regions are coupled by processes that redistribute thermal plasma throughout the system. By combining measurements of several high latitude incoherent scatter radars and DMSP satellites, they showed, on a north polar map, how the stormtime plumes of enhanced total electron content (TEC) derived from a network of GPS receivers are transported from low latitudes in the post noon sector by the subauroral disturbance electric field into mid-latitudes and eventually into the polar cap. The left panel of Figure 1 is reproduced from the Foster et al. (2005) paper while the right panel has been created as part of our ongoing study of the impact of this storm on GPS-based navigation systems. The satellites of the GPS constellation are in 12-hr circular orbits (at 20,000-km altitude) with orbital inclination of 55 degrees, giving coverage to L~4 from low-latitude receiving sites. The vertical TEC determined is the combined contribution of the ionosphere and overlying plasmasphere. For the severe disturbance event of 20 November 2003, a 2-D map of vertical TEC from a closely spaced network of ~ 450 North American GPS sites is generated. It shows an intense storm enhanced density (SED) plume with >150 TECU (1 TECU = 1.E16 electrons/m2, column density) extending NW across the northeastern USA and into Canada. The local time of this image (1945 UT) is ~1500 LT at Washington, D.C., which lies under the intense plume. During the 29–31 October 2003 superstorms (Basu et al., 2005b), similar dense plumes of SED spanned the United States, arising from regions of enhanced mid and low-latitude TEC observed below 30 degree latitude as shown in the left panel of Figure 1.

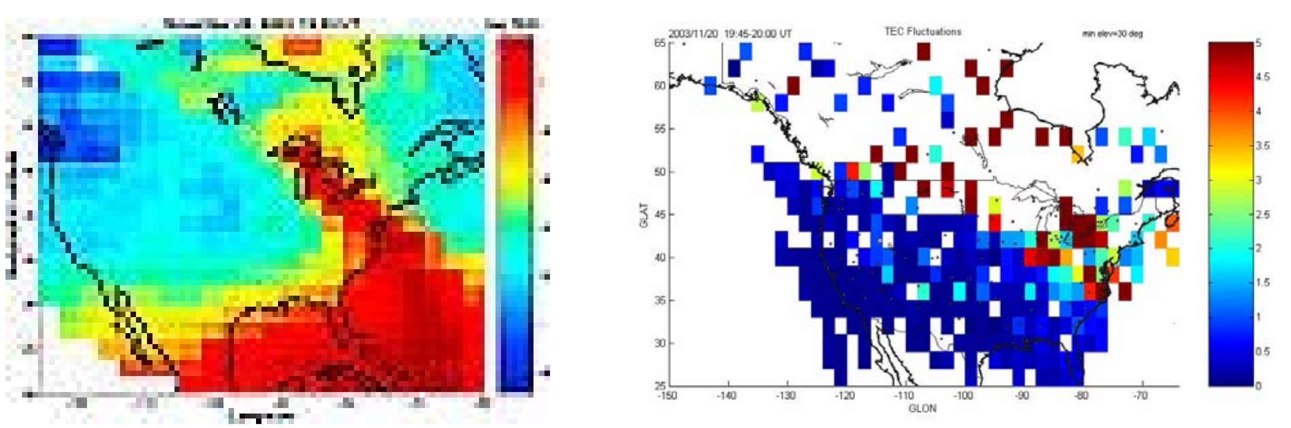

Fig 1 – A large SED plume shown on the right and TEC fluctuations along the length of the plume on the right seen across NE US on Nov 20, 2003 at 1945 UT

We have computed maps of TEC fluctuations using a subset of about 250 GPS dual-frequency stations to determine structuring at tens of km scales by utilizing TEC measurements made every 30 seconds. Two such samples are differenced to obtain one-minute values of TEC fluctuations observed at each station. Then within every 15-minute UT interval at each station, the maximum absolute value of TEC fluctuation along an individual satellite track is found from the one-minute values after imposing a minimum 30-degree elevation angle cut-off to reduce the effects of multi-path. This maximum value is assigned to the 350-km intersection point which is closest to the center of the region covered in 15 minutes; intersection points in a 15-minute interval generally move less than one degree in latitude and longitude at mid- and low-latitudes. Similar data from all stations are collected into 2° ×2° latitude-longitude bins to produce a single 15-minute map such as shown in the right panel of Figure 1. TEC fluctuations are measured in units of TECU/min. It is important to note that large amplitude TEC fluctuations, as large as 5TECU/min, are observed along the SED plume across north-eastern US and into the Hudson Bay region of Canada as shown in the left panel. It is extremely difficult for communication and navigation systems operating within the US, in particular the Wide Area Augmentation System (WAAS) developed by the Federal Aviation Administration (FAA), to function in the presence of such large amplitude TEC fluctuations. During this storm WAAS was non-operational for over 10 hours as shown in Figure 2 (Doherty et al., 2004). The other two storms where the per cent area coverage within CONUS (CONtiguous US) drops to zero were those on Oct 29, 2003 and Nov 8, 2004. Thus it is extremely important to be able to provide prediction algorithms for the initiation and the time interval for the occurrence of such fluctuations to minimize the down-time of this operational system of such great importance for US civilian and military systems.

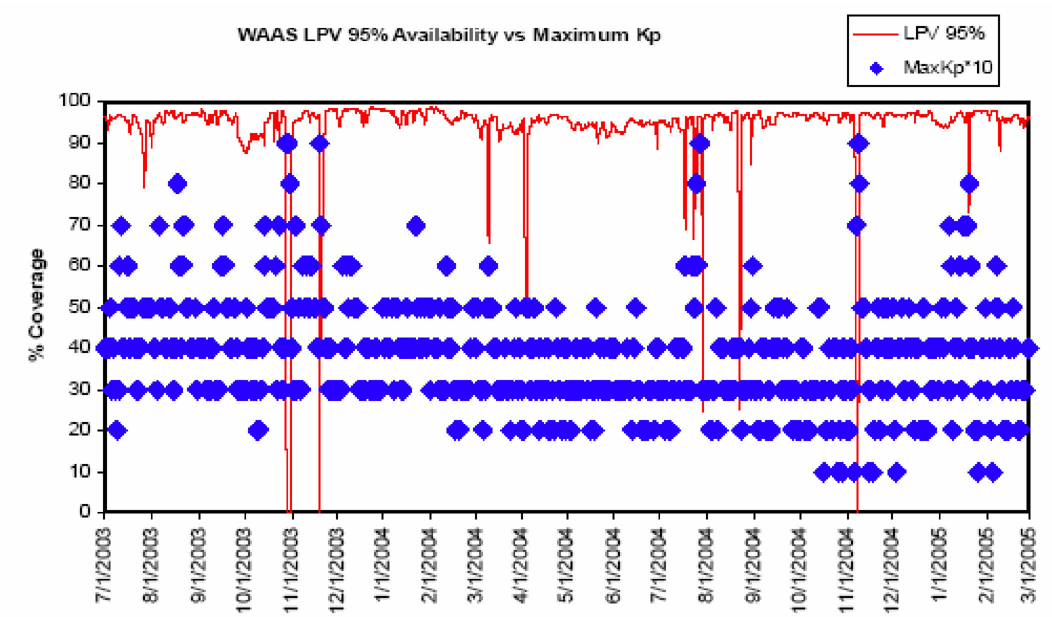

Fig 2 – WAAS was unavailable within CONUS for more than 10 hours on November 20, 2003

In addition, the IMAGE satellite has provided dramatic evidence of changes in the plasmaspheric topology during such large storms, many of which could be tracked at ionospheric altitudes by the DMSP satellites and ground-based radars. Using such coordinated measurements, Foster et al. (2002) were able to show that during the large magnetic storm that occurred on March 31, 2001, plumes of greatly enhanced TEC were associated with the erosion of the outer plasmasphere by strong sub-auroral polarization electric fields. Thus a key feature of their results was the presence of enhanced plasma convection in a sunward direction dubbed sub-auroral polarization streams (SAPS). A very prominent SAPS is seen on DMSP data throughout the dusk hours on Nov 20, an example of which is shown in Figure 3. Recently, Keskinen, Basu and Basu (2004), developed a model for small-scale ionospheric structure in the SAPS-driven density trough during magnetic storms. It is very important to continue and extend such studies for magnetic storms with different UT times for their main phase so that their effects on the WAAS system can be studied under local daytime and nighttime conditions. Such studies are currently underway.

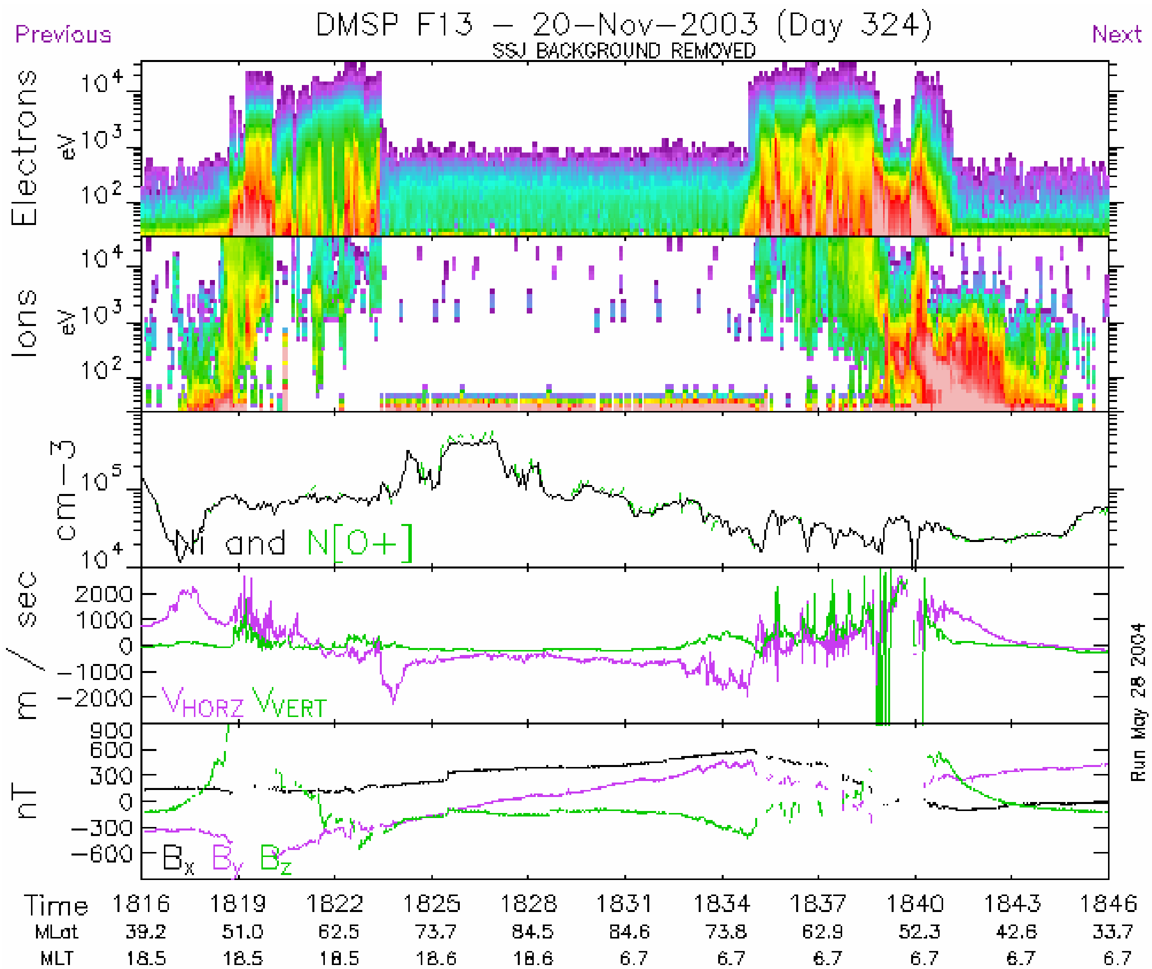

Fig 3 – DMSP F13 orbit showing evidence of SAPS on Nov 20, 2003 at 1817-1818 UT

Another very important aspect of the proposed work is to study the effects of magnetic storms on the equatorial region, where some of the largest scintillation occurs and where most of the recent military conflicts have taken place. Figure 4 shows that when the DP phase is active at mid-latitudes, creating the SED over the US and significant navigation problems (Figure 2) in conjunction with the SAPS in the northern hemisphere dusk sector (Figure 3), the equatorial ionosphere is also considerably impacted by the same DP electric field. The top panel of Figure 4 illustrates four successive DMSP F14 orbits A, B, C and D that marched from Africa through the Atlantic to the Brazilian sector during the period 1800 UT to 2315 UT on Nov 20. At the time of Dst minimum on this day, covering the period 1800 UT to 2000 UT, dusk conditions prevailed over the longitude interval of 15° E to 15° W. Orbit A at about 20° E longitude over Africa detected ion density depletions to a level of 3 x 103 cm-3 over a magnetic latitude interval of 2° N - 9° S. The next orbit B over the Atlantic to the west of Africa detected latitudinally extended ion density depletions with a minimum ion density of 4 x 103 cm-3 around the magnetic equator. Orbits C and D crossed the magnetic equator at 2140 UT and 2318 UT respectively at the beginning of the recovery phase of the storm. These two DMSP orbits did not detect any ion density depletion or bubbles. Instead these two orbits detected the crests of the equatorial anomaly around 10° N and 10° S magnetic latitudes with ion densities of about 4 x 105 cm-3.

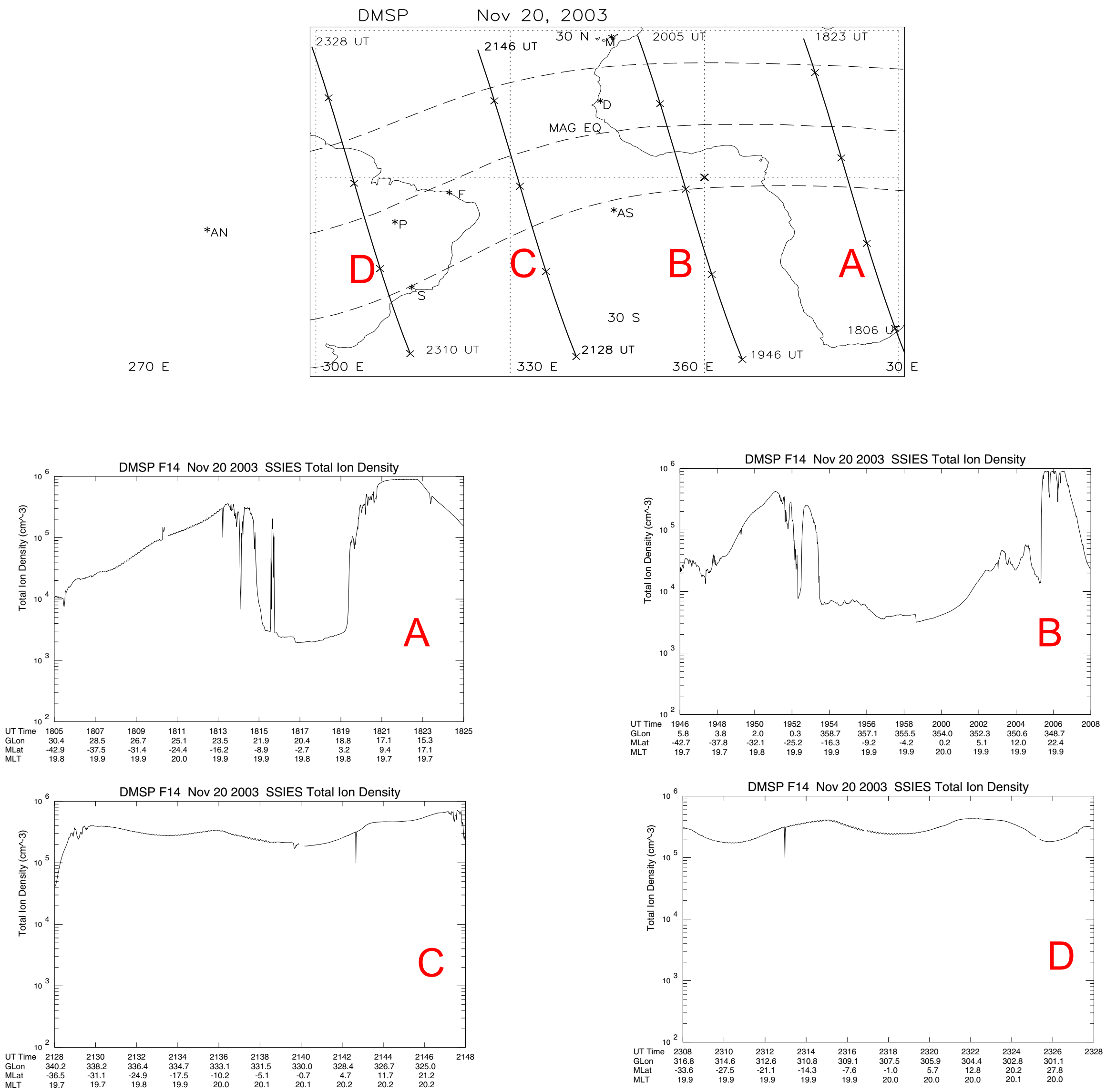

Fig 4 DMSP F14 orbits showing large depletions and plasma bubbles on Nov 20, 2003

It is important to note that orbits A and B are the only ones this night to show any perturbations over the equator. This is also the time when the Dst index has the largest variation with time indicating the existence of the DP field at the equator (Basu et al., 2001 b). Thus they follow the pattern seen with earlier storms (Basu et al., 2005b).

IMPACT/APPLICATIONS

Since a consistent pattern is emerging, related to the time-variation of the Dst index, the development of an algorithm is currently underway to identify the longitude range that is going to be affected by the development of irregularities. The fact that only a particular range of equatorial longitudes is affected during magnetic storms, which depends on the UT of the largest time-variation of the SYM-H index during the development phase, provides a basis for algorithm development for scintillation onset. This algorithm is now being developed by our AFRL colleagues. This coupling of the entire Sun-Earth system makes the understanding and prediction of magnetic storm impacts challenging. However, since the impacts are so severe on DoD communication, navigation and surveillance systems, it is worth the effort!

RELATED PROJECTS

Coordinated multi-technique measurements were conducted in support of COSMIC satellites launched in April 2006. These early measurements were organized to take advantage of the clustering of satellites in the constellation generally referred to as "beads on string" configuration. This configuration only occurs during the early phase when the satellites are around the launch altitude, approximately 500 km, before they are finally deployed at 800 km altitude. This clustered configuration permits measurements with high spatial and temporal resolution from all three COSMIC instruments, namely, the GPS occultation sensor (GOX), the Tiny Ionospheric Photometer (TIP) and the radio beacon. The main advantage of this constellation is that the coverage in latitude and longitude is unprecedented. The NRL TIP observations of nighttime 135.6 nm emission provide the features of the equatorial anomaly, namely the ionization density at the crests, the crest to trough density ratio, the latitude separation of the crests and their asymmetry. The GOX sensor is able to provide accurate electron density profiles in the equatorial anomaly region at dusk by the assimilation of TIP data on density gradients. Major ground-based support was provided by incoherent scatter radars at Jicamarca and Kwajalein, the TEC network in the South American sector and scintillation measurements from nearby SCINDA sites. The analysis of these observations will provide a significant new topic of investigation under a continuation of this Grant.

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McDonald, S., Su. Basu, S. Basu, K. Groves, C. Valladares, L. Scherliess, D. Thompson, R. Schunk, J. Sojka, and L. Zhu, Extreme longitudinal variability of plasma structuring in the equatorial ionosphere on a magnetically quiet equinoctial day, *Radio Science,* Vol. 41, RS6S24, doi:10.1029/2005RS003366, 2006.

HONORS

Sunanda Basu was invited to deliver a General Lecture on the Impacts of Extreme Solar Disturbances on the Earth's Near-Space Environment at the URSI General Assembly in New Delhi, India on October 28, 2005.